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Improvement in trunk kinematics after treadmill-based reactive balance training among older adults is strongly associated with trunk kinematics before training

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A B S T R A C T

Reactive balance training (RBT) is an emerging fall prevention exercise intervention for older adults. To better understand factors that influence improvements after RBT, the goal of this study was to identify key factors that strongly associate with training-induced improvements in reactive balance. This study is a secondary analysis of data from a prior study. Twenty-eight residents of senior housing facilities participated, including 14 RBT participants and 14 Tai Chi participants (controls). Before and one week after training, participants completed balance and mobility tests and a reactive balance test. Reactive balance was operationalized as the maximum trunk angle in response to standardized trip-like perturbations on a treadmill. Bivariate (Pearson) correlation was used to identify participant characteristics before RBT and measures of performance during RBT that associated with training-induced changes in maximum trunk angle. Maximum trunk angle before reactive balance training exhibited the strongest association with training-induced changes in maximum trunk angle among RBT participants (r^2 = 0.84; p < .001), but not among Tai Chi participants (r^2 = 0.17; p = .138). Measures of performance during RBT, based upon perturbation speed, also associated with RBT-induced improvements in maximum trunk angle. These results help clarify the characteristics of individuals who can benefit from RBT, and support the use of treadmill perturbation speed as a surrogate measure of training-induced improvements in trunk kinematics.

1. Introduction

Reactive balance training (RBT) is an emerging fall prevention exercise intervention for older adults. RBT aims to improve the kinematic response to destabilizing perturbations (i.e. reactive balance) by eliciting neuromuscular adaptations to such perturbations through repeated exposure (Gerards et al., 2017). For example, RBT involving repeated trip-like treadmill perturbations can improve trunk kinematics after trip-like perturbations (Grabiner et al., 2008), reduce fall rates after laboratory-induced trips (Bieryla et al., 2007), and reduce trip-related fall rates in the community (Rosenblatt et al., 2013).

To better understand factors that influence RBT-induced improvements in reactive balance, the goal of this study was to identify participant characteristics before RBT and measures of performance during RBT that associate with RBT-induced changes in trunk kinematics. Maximum trunk angle in response to a trip-like perturbation on a specialized treadmill was used to operationalize trunk kinematics and reactive balance. This decision was based upon the substantial mass of the trunk nearing 50% of total body mass (Winter, 2009), and the critical need to arrest the anterior rotation of the trunk to avert a fall (Crenshaw et al., 2012; Grabiner et al., 2008). The results from this study may help identify individuals who are likely to benefit from RBT, and clarify how performance during training translates to RBT-induced improvements in trunk kinematics.

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2. Methods

This study was based upon a secondary analysis of data from a prior RCT (Clinicaltrials.gov: NCT02551666) comparing the effects of treadmill-based RBT versus Tai Chi on reactive balance (Aviles et al., 2019). Participants in this secondary analysis included 28 residents of senior housing facilities who satisfied our inclusion criteria (Aviles et al., 2019). Fourteen were RBT participants who completed at least seven RBT sessions, and 14 were control participants who completed at least nine sessions of Tai Chi training (Table 1). Several participants exhibited scores on clinical tests of balance and mobility indicating an elevated fall risk (Aviles et al., 2019). The study was approved by the Texas A&M University institutional review board, and all participants provided written consent before participating.

RBT participants completed three 30-minute training sessions per week for four weeks. Each session consisted of approximately 40 trip-like perturbations, and is described in detail elsewhere (Aviles et al., 2019). Briefly, each perturbation involved participants initially standing on the treadmill belt, followed by a sudden posterior acceleration of the treadmill belt to induce a forward loss of balance. Participants attempted to prevent a fall by stepping and establishing a steady gait before the belt speed was decreased to zero to end the trial. Before the perturbation, a lightweight foam stepping block (4 $\times$ 4 cm cross section) was positioned in front of the feet to induce a step over a tripping obstacle, as would be required during actual trip recovery. Perturbation speeds were varied pseudo-randomly between 0.5 and 2.4 mph to individualize training to participant performance, to provide variability, and to progressively increase perturbation speed to continue to challenge participants as their performance improved (see online Supplemental Material for details). Anterior treadmill belt perturbations were also pseudo-randomly applied to minimize anticipation regarding perturbation direction. Participants wore a fall protection harness attached to a stationary overhead gantry during both training and testing sessions to prevent knee or hand contact with the treadmill if unsuccessful maintaining balance. Tai Chi participants completed three 30-minute training sessions per week for four weeks involving the Yang Short Form.

Before and one week after training, testing sessions were completed that included the Berg Balance Scale (Berg et al., 1992) and treadmill perturbations at standardized speeds to assess reactive balance (Table 1). During treadmill perturbations, sagittal plane trunk angle was sampled at 128 Hz using a wireless inertial measurement unit (APDM, Inc., Portland, OR, USA) worn inferior to the suprasternal notch. Trunk angle was considered 0 degrees during upright stance, and increased as the trunk flexed anteriorly. Maximum trunk angle was used to operationalize trunk kinematics and reactive balance, and was calculated over the 1.2 s immediately following perturbation onset. The mean across two 0.8 mph perturbations was used for analysis. For both groups of participants, the training-induced change in maximum trunk angle was calculated as the maximum trunk angle after training minus the maximum trunk angle before training. A decrease in maximum trunk angle after training was interpreted as an improvement in trunk kinematics and reactive balance (Grabiner et al., 2008).

Participant characteristics before training included age, body mass index, Berg Balance score, and maximum trunk angle after a trip-like perturbation (Table 1). Three measures of performance during RBT were obtained. Because perturbation speed was varied and based largely upon participant performance, the mean speed within each session was used as an indirect measure of participant performance. First, rate-of-change-of-perturbation-speed-across-RBT was calculated as the slope of a least squares fit line through the mean session perturbation speed across sessions. Second, change-in-perturbation-speed-across-RBT was calculated as the mean speed during the last two sessions minus the mean speed over the first two sessions. Third, perturbation-speed-at-end-of-RBT was calculated as the mean speed over the last two RBT sessions. Measures of performance during RBT were only calculated

Table 1
Variables explored for association with training-induced changes in maximum trunk angle. Values are mean (standard deviation).

	RBT Participants	Tai Chi Participants
Baseline characteristics		
Age (years)	82.3 (6.1)	82.9 (4.7)
Body mass index (kg/m^2)	28.6 (4.7)	31.3 (4.6)
Berg Balance score (out of 56)	46.5 (4.1)	43.6 (5.4)
Max trunk angle before training (degrees)	26.4 (9.7)	19.4 (9.5)
Performance during RBT		
Rate of Change of Perturbation Speed across RBT (m/s)/session	0.043 (0.010)	n/a
Change in Perturbation Speed Across RBT (m/s)	0.287 (0.062)	n/a
Perturbation Speed at End of RBT (m/s)	0.696 (0.077)	n/a

Note: RBT = reactive balance training. n/a = not applicable since Tai Chi participants did not perform RBT.

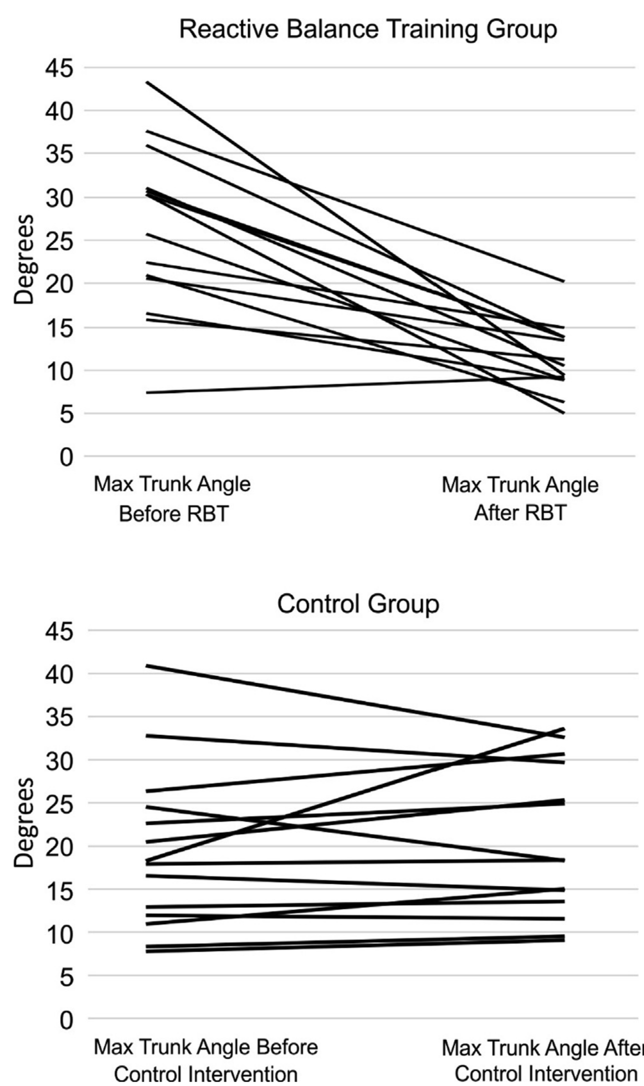

Fig. 1. Maximum trunk angle of individual participants before and after training among RBT participants (top) and Tai Chi participants (bottom).

during sessions and perturbations with the foam block, and not using warm-up or anterior belt perturbations.

Maximum trunk angle before and after training were compared within each group using a paired *t*-test. Among RBT participants, the strength of association between training-induced changes in maximum trunk angle, and both participant characteristics before RBT and performance during RBT, were determined using bivariate (Pearson) correlation and the coefficient of determination (r^2). To determine the extent to which the strongest association was due to repeated testing and not RBT itself, we correlated the same variables among the Tai Chi participants. The Holm-Bonferroni correction was used to control for the family-wise Type 1 error rate among the eight correlations performed (Holm, 1979). All statistical analyses were conducted using JMP 14 (SAS, Cary, NC).

3. Results

Among RBT participants, maximum trunk angle decreased (mean(SD)) 15.0 (9.3) degrees ($p < .001$; Fig. 1). Maximum trunk angle before training significantly associated with RBT-induced change in maximum trunk angle ($r^2 = 0.84$; $p < .001$) such that a greater maximum trunk angle before training associated with a greater reduction in maximum trunk angle (Fig. 2). Rate-of-change-of-perturbation-speed-across-RBT-sessions ($r^2 = 0.52$; $p = .003$) and change-in-perturbation-speed-across-RBT ($r^2 = 0.39$; $p = .018$) were both significantly associated with RBT-induced change in maximum trunk angle, but the latter did not meet the adjusted significance level from Holm-Bonferroni. Among Tai Chi participants, maximum trunk angle increased 1.1 (5.6) degrees ($p < .495$; Fig. 1). Moreover, their maximum trunk angle before training did not significantly associate ($r^2 = 0.17$; $p = .138$) with the training-induced change in maximum trunk angle.

4. Discussion

Maximum trunk angle before training exhibited the strongest association with training-induced change in maximum trunk angle among RBT participants. The negative correlation coefficient indicated that the poorer performers before training (higher maximum trunk angle) improved more than the better performers before RBT. Given the lack of such association among Tai Chi participants, RBT-induced improvements in maximum trunk angle were unlikely to have resulted from mere repeated testing or regression toward the mean. This leads to the encouraging conclusion that RBT was able to improve reactive balance among the poorer performers within our sample.

The rate of change of perturbation speed across RBT sessions was also significantly associated with training-induced change in maximum trunk angle. This provides clinical utility by supporting the use of easily-accessible measurements of treadmill perturbation speed as an indicator of trunk kinematic improvements without the need for trunk instrumentation.

Three limitations warrant discussion. First, if the maximum trunk angle assessment was not challenging enough to participants, the better performers before training had limited capacity to improve their maximum trunk angle. Such a ceiling effect on maximum trunk angle could provide some explanation for the association between maximum trunk angle before training and training-induced change in maximum trunk angle. While we cannot rule this out, we elected to not include data we obtained at higher perturbation speeds because over 40% of RBT participants could not successfully recover from perturbations at the next highest perturbation speed (1.6 mph) at baseline, and over 70% could not recover from perturbations at the highest perturbation speed (2.4 mph) at baseline. Despite this potential ceiling effect, RBT still appears to be worthwhile and elicit improvements in reactive balance among the better performers before training. The three best performers before training, for example, all exhibited at least one top 50th percentile improvement in maximum trunk angle at 1.6 mph after RBT or in general training progressions during RBT. Second, it is unclear how these results generalize beyond the sample and specific RBT regimen investigated here, as well as to actual falls. However it is notable that the mean reduction in maximum trunk angle after RBT was comparable to the 14-degree lower maximum trunk angle after successful, compared to failed, recoveries from similar treadmill perturbations (Crenshaw et al., 2012). Third,

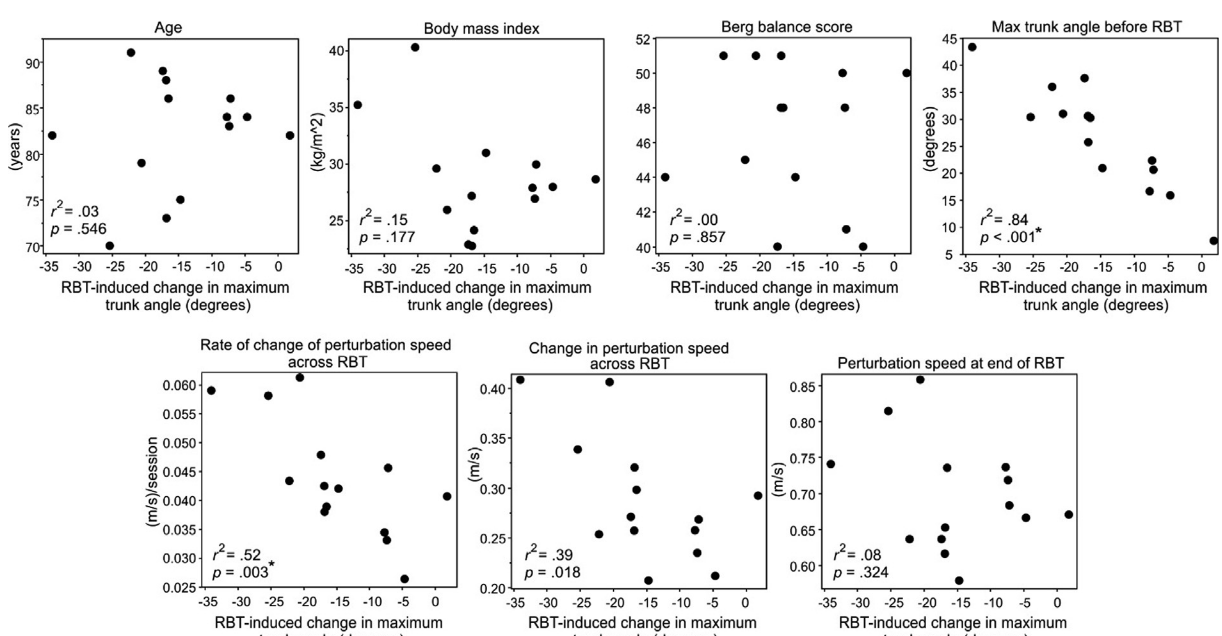

Fig. 2. Scatter plots and strength of associations with RBT-induced changes in maximum trunk angle among RBT participants. RBT = reactive balance training. * statistically significant after the Holm-Bonferroni correction for multiple comparisons.

other participant characteristics not investigated here may also be useful in predicting RBT-induced changes in maximum trunk angle (e.g. lower limb power).

In conclusion, older adults with poorer reactive balance before RBT improved more with RBT than those with better reactive balance before RBT. Perturbation speed during RBT was also indicative of improvements in trunk kinematics after RBT. These results help clarify the characteristics of individuals who can benefit from RBT, and support the use of treadmill perturbation speed as a surrogate measure of training-induced improvements in trunk kinematics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2020.110112.

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